

Photopolarimetric monitoring of 41 blazars in the optical and near-infrared bands with the Kanata telescope

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Blazars are a kind of active galactic nuclei (AGN) in which a relativistic jet is considered to be directed along the line of sight. They are characterized by strong and rapid variability of the flux and high polarization. We performed a monitoring of 41 blazars in the optical and near-infrared regions from 2008 to 2009 using TRISPEC attached to the “Kanata” 1.5-m telescope. In this paper, we report the correlation of the flux, color and polarization using our data, and discuss universal features for blazars, which have not fully been established. Three blazars (3C 454.3, QSO 0454–234, and PKS 1510–089) tended to be redder when they were brighter, only during their faint states. This color behavior suggests that the contribution of a thermal component is strong in the faint states for those objects. Excluding this “redder-when-brighter” phase, we found that 24 blazars tended to be bluer when they were brighter. This number corresponds to 83% among well-observed objects which we observed for > 10 nights. Thus, we conclude that the “bluer-when-brighter” trend is a universal feature for blazars. On the other hand, the correlation of the flux and the polarization degree is relatively weak; only 10 objects showed a significant positive correlation. We also investigated the luminosity-dependence of the color and polarization, and found that lower luminosity objects have smaller variation amplitudes both in the flux, color, and polarization degree.

1. Introduction

Blazars are one of subgroups of active galactic nuclei (AGN). They have a relativistic jet which is considered to be directed along the line of sight. The emission from blazars can be observed in a very wide range of wavelength from the radio to TeV γ -ray regions, with a strong variability in various timescales. Their spectral energy distribution (SED) is characterized by non-thermal continuum spectra with broad low and high energy components. The low energy component is believed to be synchrotron radiation by relativistic electrons in the jet. The origin of the high energy component is not fully understood, while the most plausible source is the emission via inverse Compton scattering of the synchrotron emission and/or external photons.

Blazars have been classified into three categories: high-energy peaked BL Lac object (HBL), intermediate-energy peaked BL Lac object (IBL) and low-energy peaked BL Lac object (LBL). The SED of the synchrotron component has a peak at a frequency lower than the optical region in LBL, while it is higher in HBL. The peak frequency is around the optical–infrared region in IBL.

The mechanism of variations in blazars has been extensively studied with the variation in color. Carini et al. [1992] reported a possible feature that both BL Lac (LBL) and OJ 287 (IBL) became bluer when they were brighter (Clements et al. [2001]). Ghisellini et al. [1997] observed S5 0716+714 (IBL), and found that a bluer-when-brighter feature was seen only in its “low” state. In this object, the bluer-when-brighter feature was later found in variations

having a time-scale shorter than a few days in its “high” state (Wu et al. [2007]; Sasada et al. [2008]). Villata et al. [2002] and Villata et al. [2004] reported that the bluer-when-brighter feature in BL Lac was only observed for short-term variations, and not prominent in long-term ones. Raiteri et al. [2001] performed multi-band photometric observations of AO 0235+164 (LBL) for four years, and found a bluer-when-brighter trend in this object.

Systematic studies for several blazars have also been performed in order to establish a common behavior of color variations in blazars. Ghosh et al. [2000] performed the observations of five blazars. 3C 66A (IBL) only exhibited a bluer-when-brighter trend in their sample, while the other objects showed no significant correlation of the flux and color. Gu et al. [2006] investigated the color variation of eight blazars. Bluer-when-brighter features were confirmed in five blazars. Among the other three objects, 3C 345 (LBL) showed no correlation of the flux and the color was detected, and 3C 454.3 (FSRQ) and PKS 0420–01 (FSRQ) showed a reddening trend when they were brightening. This trend is called “redder-when-brighter”, and has been confirmed in 3C 454.3 (Raiteri et al. [2008], Villata et al. [2006]). Thus, it is currently unclear whether the bluer-when-brighter feature is a universal one in blazars.

Only few cases have been reported in which the polarization degree correlates with the flux. In general, the temporal variation of polarization is considered to be erratic in blazars (e.g. Moore et al. [1982]). The polarization degree of Mrk 421 (HBL) increased to $\sim 14\%$ associated with its outburst in 1997 (Tosti et al. [1998]). A significant correlation of

the flux and the polarization degree was also detected in AO 0235+164 in 2006 (Hagen-Thorn et al. [2008]). Dense and long-term polarimetric observations are required in order to find a possible universal relation of the flux and polarization in blazars.

The *Fermi* Gamma-ray Space Telescope was launched in June, 2008. *Fermi* can measure a γ -ray spectrum from 30 MeV up to 300 GeV. At this occasion, we performed the photopolarimetric monitoring of blazars in the optical and near-infrared bands using TRISPEC attached to the Kanata telescope of the Higashi-Hiroshima Observatory. In this paper, we report the results of the observations with Kanata. We investigated the relation of the luminosity, color and polarization degree.

2. Observation

We performed observations of 41 blazars in the optical V and the near-infrared J and K_s bands using TRISPEC attached to the 1.5-m “Kanata” telescope at Higashi-Hiroshima Observatory since May 2008. We selected the monitored blazars from the catalog, “Extended list of 206 possible AGN/blazar targets for GLAST multifrequency analysis”¹ with an apparent magnitude of $R \lesssim 16$. The number of the selected objects is 30 in this catalog. New objects were occasionally added in our sample when *Fermi* detected a *gamma*-ray activity of them, or when optical flares were detected. The number of the additional objects is 11. Table I lists our objects.

TRISPEC is capable of simultaneous three-band (optical one and near-infrared two bands) imaging or spectroscopy, with or without polarimetry (Watanabe et al. [2005]). TRISPEC has a CCD and two InSb arrays. An one polarization data point is obtained from four images which are obtained using the half-wave plate in the differential angles. The magnitudes were measured using the aperture photometry technique. Then, we calculate the differential magnitudes of objects with a comparison star taken in the same frame. The magnitudes of the comparison stars were referred from Skiff et al. [2007], Hog et al. [2000], Villata et al. [1998], González-Pérez et al. [2001], Adelman-McCarthy et al. [2009], Doroshenko et al. [2005], Cutri et al. [2003].

In a night, we obtained 12 sets of images for an object, from which three sets of polarimetric parameters were obtained. Exposure times depend on the sky condition and the apparent magnitude of objects, typically 50–200 s, 5–20 s, and 2–5 s in the V , J and K_s band, respectively. Since we make no discussion

Table I Observation log.

The columns are :(1)the object name; (2)the blazar class; (3)the observation period; (4)the number of observation nights.

object (1)	class (2)	observation period (3)	n (4)
Mis V1436	FSRQ	08 Dec.17 - 09 Nov.28	90
PKS 0215+015	FSRQ	08 Sep.28 - 09 Aug.25	6
QSO 0324+341	FSRQ	08 Nov.25 - 09 Oct.14	2
QSO 0454-234	FSRQ	08 Oct.14 - 09 Nov.21	53
OJ 49	FSRQ	08 Oct.21 - 09 Nov.29	38
QSO 0948+002	FSRQ	09 Mar.29 - 09 Apr.10	3
3C 273	FSRQ	08 Dec.10 - 09 Nov.29	59
QSO 1239+044	FSRQ	09 Jan.29 - 09 Feb.16	7
3C 279	FSRQ	08 Dec.16 - 09 Jul.14	61
PKS 1502+106	FSRQ	08 Aug.14 - 09 Jun.26	71
PKS 1510-089	FSRQ	09 Jan.26 - 09 Jul.22	52
3C 454.3	FSRQ	08 May22 - 09 Nov.29	226
1ES 0323+022	HBL	08 Jul.29 - 09 Oct.26	23
1ES 0647+250	HBL	08 Sep.26 - 09 Mar.17	6
1ES 0806+524	HBL	08 Oct.17 - 09 Nov.17	14
Mrk 421	HBL	08 Jun.17 - 09 Mar.31	42
ON 325	HBL	08 May31 - 09 Nov.23	45
PG 1553+113	HBL	08 Jul.23 - 09 Sep.18	21
H 1722+119	HBL	08 Jul.18 - 09 Oct.17	28
1ES 1959+650	HBL	08 Jul.17 - 09 Nov.28	53
PKS 2155-304	HBL	08 Jul.28 - 09 Nov.28	130
1ES 2344+514	HBL	08 Jul.28 - 09 Oct.11	17
PKS 0048-097	IBL	08 Oct.11 - 09 Sep.23	46
S2 0109+224	IBL	08 Jul.23 - 09 Oct.29	74
3C 66A	IBL	08 Jul.29 - 09 Nov.29	194
PKS 0422+004	IBL	08 Sep.29 - 09 Nov.11	42
S5 0716+714	IBL	08 May11 - 09 Nov.29	203
PKS 0754+100	IBL	08 Nov.29 - 09 Mar.18	28
OJ 287	IBL	08 May26 - 09 Nov.29	191
ON 231	IBL	08 Dec.29 - 09 Feb.02	5
Mrk 501	IBL	08 May02 - 09 Sep.19	40
PKS 1749+096	IBL	08 Jul.19 - 09 Sep.10	78
3C 371	IBL	08 Jul.10 - 09 Nov.17	100
AO 0235+164	LBL	08 Jul.17 - 09 Jul.22	71
S5 1803+784	LBL	08 Jul.22 - 09 Oct.18	35
BL Lac	LBL	08 May18 - 09 Nov.27	189
OQ 530	unknown	08 Jul.27 - 08 Sep.10	3
PKS 1222+216	unknown	09 Apr.10 - 09 Apr.22	1
RX J1542.8+612	unknown	09 May22 - 09 Nov.19	59
S4 0954+65	unknown	08 Dec.19 - 09 Jan.07	2
3EG 1052+571	unknown	08 Oct.07 - 09 Oct.13	3
4C 14.23	unknown	09 Oct.13 - 09 Nov.26	14

¹<http://glastweb.pg.infn.it/blazar/>

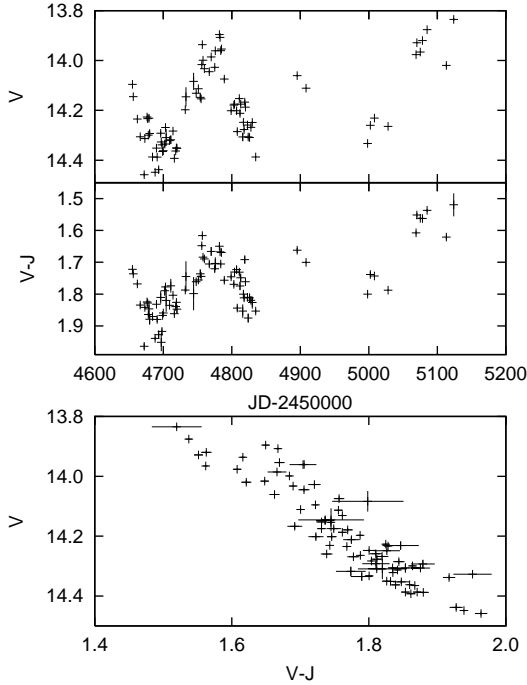


Figure 1: Our results for 3C 371. Top and middle panel: The lightcurve and the color variation. Bottom panel: The color-magnitude diagram.

about intra-night variability in this paper, we only use nightly-averaged photometric and polarimetric data.

3. Results

3.1. Lightcurve and Color

We show an example of the light curve and the color-magnitude diagrams in figure 1. This figure shows the result for 3C 371. As shown in figure 1, the object became bluer when it was brighter. We calculated correlation coefficients between the magnitude and the color index for 41 blazars, and then performed t -test for the significance of the correlation. As a result, we found that 21 blazars exhibited a significant bluer-when-brighter feature.

We found that three blazars (3C 454.3, PKS 1510-089 and QSO 0454-234) tended to be redder when they were brighter for their faint states. For example, figure 2 shows the lightcurve and color-magnitude diagram of 3C 454.3. A redder-when-brighter trend appeared when it was fainter than $V \sim 15$. Those three objects showed a significant bluer-when-brighter feature in the case that we only used the data brighter than $V = 15$, 15.6 and 16.0 for 3C 454.3, PKS 1510-089 and QSO 0454-234, respectively. The number of objects showing a bluer-when-brighter feature is, hence, 24 with those three objects.

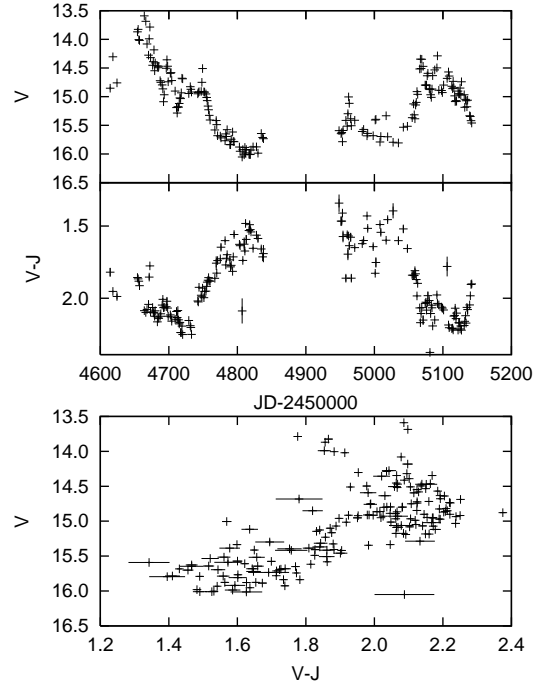


Figure 2: Our results for 3C 454.3. Top and middle panel: The lightcurve and the color variation. Bottom panel: The color-magnitude diagram.

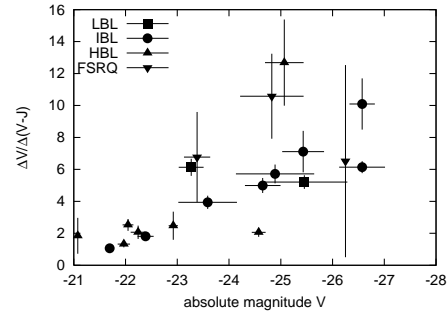


Figure 3: $\Delta V/\Delta(V-J)$ against the V -band absolute magnitude of 23 blazars. The absolute magnitudes are averages of all data we observed for each object. This figure only includes objects in which a significant bluer-when-brighter was detected.

There are 17 blazars which showed no significant correlation between the V -band magnitude and the $V-J$ color. The numbers of observation are quite small for most of these 17 objects; it is less than 10 d for 12 objects. There are 5 blazars that was observed for > 10 d and no significant correlation of the light curve and color: OJ 287, PG 1553+113, H 1722+119, S5 0716+784 and RX J1542.8+612. Without the objects which were observed for < 10 d, the sample reduces to 29 blazars, among which 24 blazars showed significant bluer-when-brighter features. This corresponds to 83 % of the sample

Thus, our observation strongly indicates that the

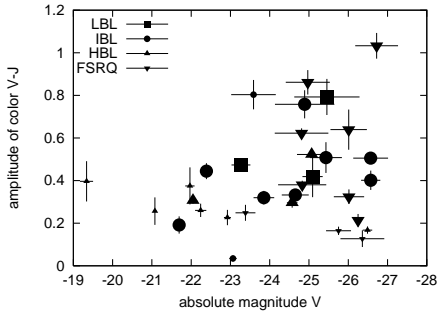


Figure 4: Peak-to-peak amplitudes of $V - J$ against the V -band absolute magnitudes of 38 blazars. The size of the symbol means the number of the observations. The small symbols: the objects observed for < 30 d. The large symbols: the objects observed for > 30 d.

bluer-when-brighter feature is a common characteristics of most of blazar variations.

We calculated the slope in the color-magnitude diagram, $\Delta V / \Delta(V - J)$, by fitting a linear function to the observed V and $V - J$ of objects that exhibited a significant bluer-when-brighter feature. $\Delta V / \Delta(V - J)$ is considered as an index of the flux variability against the color variation. This can have an advantage to investigate the variability because the observed amplitudes of variations in V and $V - J$ highly depend on the observation period.

Figure 3 shows $\Delta V / \Delta(V - J)$ against the average of the V -band absolute magnitude. While there are 24 objects which showed a significant bluer-when-brighter feature, this figure includes 23 blazars because the redshift, z , of S2 0109+224 is unknown. As can be seen in figure 3, a lower luminosity object, like HBLs, tend to have a lower $\Delta V / \Delta(V - J)$. This result suggests that the variation amplitude of the flux is smaller in lower luminosity objects.

Figure 4 shows the relation of the observed amplitudes of the $V - J$ variation and absolute magnitudes in the V -band for 38 blazars whose z is known. In this figure, the size of the symbols represents the number of observations. The objects observed for < 30 d and > 30 d are shown by the small and large symbols, respectively. There is no objects which have both a low luminosity and a large amplitude. This feature is still seen even if the objects that was observed for < 30 d are excluded. Hence, our observation suggests that the variation amplitudes are smaller in the objects with lower luminosities, like HBLs, both in the magnitude and the color.

3.2. Lightcurve and Polarization

As well as the correlation of the flux and the color, we investigated the correlation of the flux and the polarization degree. We show an example of the light curve and the polarization degree in figure 5. This

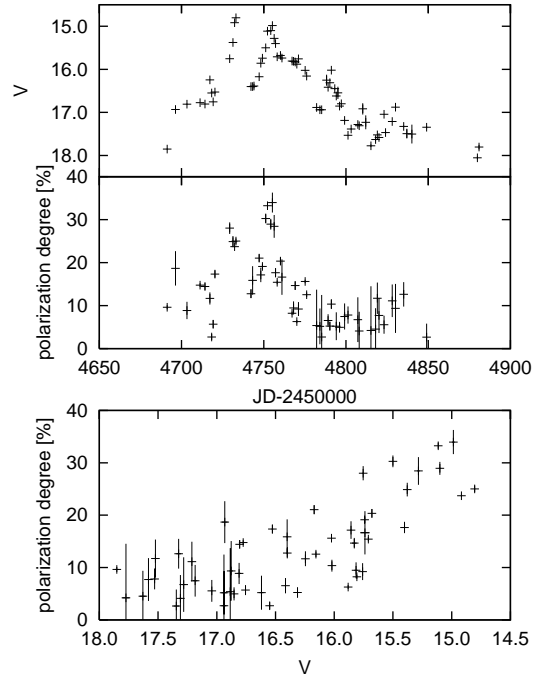


Figure 5: Our results for AO 0235+164. Top and middle panel: the lightcurve and the polarization degree variation. Bottom panel: the relation of the flux and the polarization degree.

figure shows the results for AO 0235+164. As shown in figure 5, the polarization degree of this object became high when it was brighter. We found that 10 blazars exhibited a significant correlation of the flux and the polarization degree.

We found that four blazars (QSO 0454-234, OJ 49, ON 325, and OJ 287) showed a significant anti-correlation of the flux and the polarization degree. For example, figure 6 shows the lightcurve and the polarization degree of OJ 287. In this case, the polarization degree was lower when the object was brighter.

As well as in subsection 3.1, the sample reduces to 29 blazars without the objects which were observed for < 10 d. The numbers of the objects showing significant positive and negative correlation correspond to 34 % and 14 % of the sample, respectively. The correlation of the flux is weak in the polarization degree compared with that in the color.

Figure 7 shows the average of the absolute magnitudes and the maximum value of the polarization degree of 39 blazars. The polarization degree kept low in the blazars with low luminosities, like HBLs, while prominent flares of the polarization degree were observed in the blazars with high luminosities. The variation amplitude of the polarization degree was also high/low for the high/low-luminosity blazars, since the minimum polarization degree reached to 0-5% even in the high-luminosity objects.

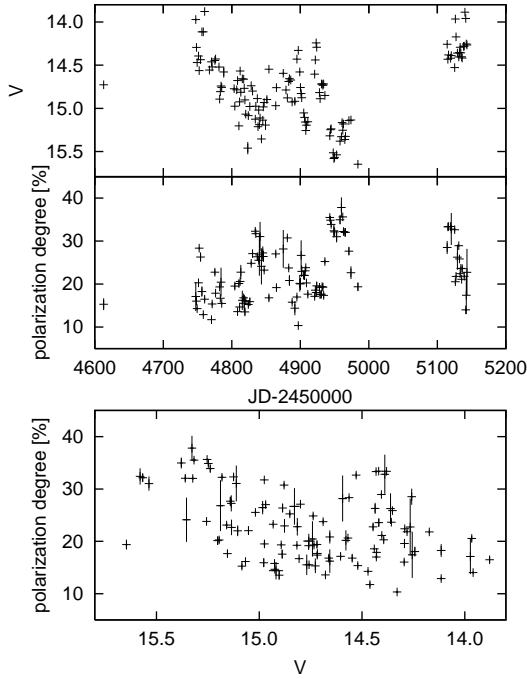


Figure 6: Our results for OJ 287. Top and middle panel: the lightcurve and the polarization degree variation. Bottom panel: the relation of the flux and the polarization degree.

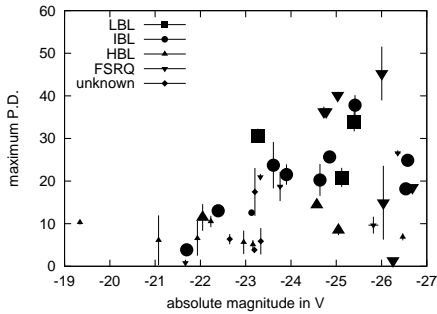


Figure 7: Maximum polarization degree against the V-band absolute magnitudes of 38 blazars.

4. Discussion

4.1. Lightcurve and Color

Kirk et al. [1998] propose that the bluer-when-brighter trend indicates an energy injection event in the emitting region. As a result of the energy injection, the number of high energy electrons increases, and thereby, the synchrotron flux in short wavelengths increases more than that in long wavelengths. The most plausible scenario for the energy injection mechanism is the internal shocks between relativistic shells (e.g. Zhang et al. [2002]). We detected a significant bluer-when-brighter feature in 83 % objects in our sample. This high fraction suggests that most of

variations in blazars are caused by the internal shock in the jet. Since our observation lasted for $\lesssim 1$ yr, we have no information about the color-flux correlation in variations having a time scale longer than $\gtrsim 1$ yr.

A universal relation between the flux and color has not been established because several objects were reported to exhibit a redder-when-brighter trend or no significant correlation of the flux and color (Gu et al. [2006]; Villata et al. [2006]; Raiteri et al. [2008]). Actually, our observation also detected clear redder-when-brighter trends in three objects, while they appeared only in faint states of each object. This redder-when-brighter behavior in the faint states is consistent with the scenario that the contribution of the thermal emission from the accretion disk becomes strong when the synchrotron emission from the jet weakened (Villata et al. [2006]). Even in our redder-when-brighter objects, our observation revealed that the bluer-when-brighter feature appeared when they brightened. Hence, the bluer-when-brighter trend is presumably a universal feature for synchrotron flares in blazars.

An alternative scenario for the variations of the flux is the change in the beaming factor of the emitting region. In this scenario, the flux from a beamed emitting region should increase in all wavelengths. Our results show that the variation amplitude of the flux and color trend to be smaller in HBL than that in LBL. This implies that the variation amplitude originated from low-energy electrons is small compared with that from high-energy electrons. Thus, our results support the internal shock scenario rather than the scenario with the beaming-factor changes for most variations in blazars.

4.2. Lightcurve and Polarization

The weak correlation of the flux and the polarization degree may be caused by the presence of two or more components in the polarization. Polarization variations correlating with the flux could be hidden in the case that there is another polarization component whose temporal variation is independent of the total flux. Based on this picture, we have developed a method to separate the observed polarization into two components which correlate and not-correlate with the flux variation (Uemura et al. [2010]). Applying this method to our blazar data, we found that the behavior of polarization in several blazars can be explained with this two-component picture.

5. Summary

We performed photopolarimetric monitoring of 41 blazars in the optical and near-infrared bands using

the Kanata telescope. Our findings are summarized below:

- The bluer-when-brighter trend was observed in 24 blazars which correspond to 83 % of our well-observed sample. Our observation strongly indicates that the bluer-when-brighter trend is a universal feature in blazars.
- Three blazars showed the redder-when-brighter trend when they were in faint states. Even in those three objects, the bluer-when-brighter trend appeared when they were in bright states.
- We found that the variation amplitudes were smaller in the objects with lower luminosities, like HBLs, in the magnitude, color, and polarization degree.
- The significant correlation of the flux and the polarization degree was observed in 10 blazars which correspond to 34 % of our well-observed sample. The correlation with the flux is weak in the polarization compared with that in the color.

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